Acceleration Mode Development for Parallel-Series Hybrid Electric Vehicle

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ABSTRACT

As the regulations for fuel efficiency and vehicle emissions increase, the demand for more innovative fuel efficient vehicles grows. The term hybrid electric vehicle has become an everyday term, however; only 3.8% of cars sold in 2013 were hybrid or electric vehicles. A newer category of hybrids is the plug in hybrid electric vehicle, which is generally capable of driving in an all-electric mode and as a hybrid. A prominent challenge with plug-in hybrids is maintaining expected vehicle performance while achieving maximum energy efficiency. The goal of this research project was to develop an acceleration mode to meet performance and consumer acceptability targets for the Ohio State EcoCAR 2 plug-in hybrid electric vehicle. When defining the acceleration mode, it was necessary to evaluate the team determined acceleration targets. These targets were to accelerate the vehicle in both all-electric and hybrid modes from 0-60 MPH in 11.5 seconds and from 50-70 MPH in 10 seconds. The acceleration modes in both all-electric and hybrid modes were also expected to meet acceptable consumer standards for everyday driving. Based on the requirements, the acceleration modes were developed to meet all performance targets. Each mode operates similarly, but has different entrance and exit conditions. In developing the performance modes, it was necessary to evaluate the maximum component operating conditions to avoid causing any possible vehicle faults. The initial mode operation and algorithm development was done

using in a Software-in-the-Loop simulator, where the impact of each modification could be easily tracked. Fault testing and timing was done using a real time Hardware-in-the-Loop simulator. The final validation and calibration will be done in the vehicle. Initial development has shown that the vehicle, in simulation, is able to enter and exit each acceleration mode and that the 0-60 MPH acceleration mode is able to achieve the acceleration target of 11.5 seconds. In taking the time to focus on hybrid vehicle performance the hope is that in the future consumers will consider plug-in hybrid electric vehicles both efficient and enjoyable to drive. This will increase the number of fuel efficient and low emissions vehicles on the road.

DEDICATION

I would like to dedicate this thesis to my incredibly supportive parents and younger sister.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Shawn Midlam-Mohler for his guidance and support of this research project. I would like to thank Dr. Giorgio Rizzoni for his ongoing support of my involvement at car and on the EcoCAR team. This project would not have been possible without the EcoCAR 2 team, especially Katherine Bovee who has continuously helped me learn and understand the EcoCAR modeling, simulation, and controls. I would also like to thank Matt Yard who was incredibly helpful in gaining a better understating of the vehicle components and operation. I would also like to thank my family and friends who have been supportive throughout this project.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

EcoCAR 2 is a three year competition sponsored by the U.S. Department of Energy and General Motors. The goal of the three year competition is for university students to redesign and build a 2013 Chevrolet Malibu that reduces fuel consumption, well-to-wheel greenhouse gas and tail pipe emissions, while still maintaining consumer acceptability. Year 1 of the competition is focused on deign and simulation, Year 2 is focused on vehicle integration, and Year 3 is focused on vehicle refinement.

The Ohio State EcoCAR 2 team is developing a Parallel-Series Plug-in Hybrid Electric Vehicle (PHEV) capable of 50 miles of all-electric range. The vehicle includes two 80 kW electric machines and a 19.8 kW Li-Ion battery pack. The large battery pack and two electric machines allows for the vehicle to operate at all expected vehicle speeds in the all-electric operating mode. The range extending operation in both series and parallel hybrid configurations is made possible by a 1.8L E85 engine and a 6-speed automated manual transmission. The unique 6-speed automated manual transmission allows for the vehicle to operate in the most efficient vehicle modes at a wide range of speeds.

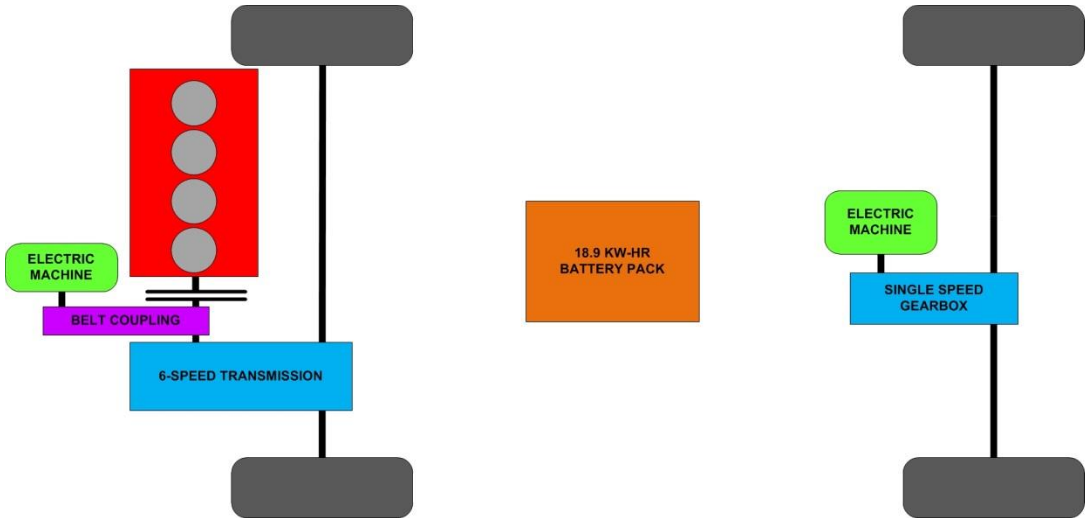

Figure 1.1: OSU EcoCAR Vehicle Figure Architecture

Because of the complex vehicle architecture shown in Figure 1.1, the OSU EcoCAR vehicle is able to operate in three main vehicle modes and a number of specialized modes. The first mode is the all-electric charge depleting (CD) mode which allows the vehicle to operate like an electric vehicle. This mode uses both electric machines to drive the vehicle. The front electric machine (FEM) is connected to the wheels through a 6-speed transmission and the rear electric machine (REM) is connected to the rear wheels through a single speed gearbox. The electric machines are capable of producing a peak torque of 180 Nm each. For normal CD driving, the torque is split between the FEM and the REM based on motor efficiency and driver requested torque. The vehicle is able to meet all speed and performance targets in the all-electric mode which can be used until the battery state of charge (SOC) reaches 20%. The goal is that the vehicle will be able to obtain an all-electric range of 50 miles.

Once the battery SOC drops below 20%, the vehicle can continue driving in one of the two charge sustaining modes. In general, a charge sustaining hybrid utilizes both an internal combustion engine (ICE) and one or more electric motors. The energy source is mainly a liquid fuel and the battery SOC remains around 20 %. Another name for a charge sustaining mode is blended mode because the two energy sources, liquid fuel and electricity, are blended to allow the engine to operate at its most efficient points which corresponds to using less fuel. At low speeds the vehicle will operate the charge sustaining series mode. In a series hybrid, the ICE is used as a generator and is mechanically connected to the FEM to generate electricity. The front powertrain is disconnected from the wheels and the REM is used to drive the rear wheels.

When the vehicle is operating in charge sustaining mode and is driving faster than 35 MPH, it operates as a parallel hybrid vehicle. In a parallel hybrid vehicle both the FEM and the ICE are connected to the wheels through a transmission. The REM is used in the same way as above to drive the rear wheels. The power at the wheels is the sum total of power from the front and rear powertrains. In all three main driving modes, the vehicle is able to utilize regenerative braking to capture back a small amount of kinetic energy when the vehicle is braking.

The vehicle is also able to operate in an acceleration mode as well as a number of limp home modes which allow the vehicle to operate under limited power or limited components if a mild fault occurs. The failure modes are in place ensure that even if there is a component failure, the customer has the ability to drive the vehicle to a safe place. The acceleration modes were developed to improve vehicle performance.

1.2 Motivation

The EcoCAR 2 competition challenges students to focus on the major concerns in the automotive industry and develop innovative hybrid vehicle technologies. The first concern is automotive energy usage which is regulated through fuel economy in the US. The Corporate Average Fuel Economy (CAFE) standards are regulations put into place by congress in 1975 when the US was experiencing an energy crisis. For many years, when the supply and cost of oil and gas were not a concern in the US, this standard was not updated. In 2012, CAFE standards were updated by the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) through 2025. Each automotive company must have an average combined fuel economy of 34.9 MPG by the end of 2014 and must improve that number to 55.4 MPG by 2025 [1]. This aggressive goal is pushing automotive manufacturers to find different ways to reduce fuel consumption. Hybrid electric vehicles (HEV) utilize many fuel minimizing technologies and PHEVs and electric vehicles (EVs) have the availability to drive, at least partially, without using liquid fuel. Many traditional hybrids use different ways to improve engine efficiency such as engine start-stop and only operating the engine at its most efficient points.

The second goal of EcoCAR 2 is to reduce tailpipe emissions. Tailpipe emissions, as defined and regulated by the EPA, are specific pollutants emitted automobiles. The EPA regulates hydrocarbons, nitrogen oxides, and particulate matter which are the products of the combustion in the engine [2]. Many of the same hybrid vehicle technologies that help improve fuel economy also improve vehicle tailpipe emissions. PHEVs and EVs have the ability to operate without any tailpipe emissions.

The last goal of the competition is to maintain or improve consumer acceptability. This includes expected vehicle performance, drivability, and interior/exterior appearance. In most production hybrids the interior and exterior of the vehicle will meet consumer standards. The concern comes when evaluating vehicle performance metrics such as acceleration. The focus of most hybrids is efficiency, often times at the expense of performance. Vehicle performance is the motivation for this project because in general consumers expect hybrid vehicles to be slower than their traditional vehicle counterparts. With only 3.8% of new vehicles sold in 2013 being hybrids or electric vehicles, there is a need to show the average customer that they can have a fuel efficient car that is still enjoyable to drive [3].

1.3 Project Objective

The focus of this project was to develop an acceleration mode for the Ohio State EcoCAR 2 Parallel-Series Plug-in Hybrid Electric Vehicle. When defining the acceleration mode, it was necessary to evaluate the team and competition acceleration targets. The EcoCAR 2 competition includes two acceleration events, 0 to 60 MPH and 50 to 70 MPH. Any acceleration completed in normal vehicle operating modes were also expected to meet acceptable consumer standards for everyday driving.

Included in the following document are background on the Ohio State EcoCAR 2 vehicle as well as other hybrid vehicles, Chapter 3 discusses the controls development process that was followed to meet the objective of the project. Chapter 4 details the development of the acceleration strategy as well as the vehicle restrictions on the performance. Chapter 5 includes the tested acceleration modes and results. The concluding chapter summarizes the implications of this research project as well as future development possibilities for this project.

CHAPTER 2: LITERATURE REVIEW

2.1 Hybrid Vehicle Architectures

The formal definition of a hybrid is "a vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently" [4]. An electrified powertrain with electric machines and an engine can be configured in many different ways to best utilize different benefits of having a hybrid. The most relevant hybrid vehicle architectures are the series, parallel, and power-split configuration. The electric machines are used as either a motor or a generator. A motor converts electrical energy to mechanical energy and a generator converts mechanical energy to electrical energy [5].

In a series hybrid vehicle the engine's torque output is converted into electrical energy using a generator and stored in a battery pack. The vehicle is driven by the electric motors using electrical energy for the battery pack. The motor can be also used as a generator for regenerative braking. The series configuration can be looked at as being closer to a pure electric vehicle because the vehicle is propelled using electrical energy [6]. This configuration allows the engine to operate at more ideal conditions because it has no mechanical connection to the wheels and therefore can operate at more efficient operating points at all times. The series vehicle architecture is shown in Figure

2.1. In the parallel hybrid vehicle configuration shown in Figure 2.2, the engine and motor are mechanically connected to the wheels through a transmission. The figure below is a pre-transmission parallel hybrid where either the engine or the electric motor can be used together or separately to propel the vehicle. With the ICE being mechanically connected to the wheels, a downside of the parallel vehicle configuration is that the ICE may not be controlled to operate at only the most ideal operating conditions.

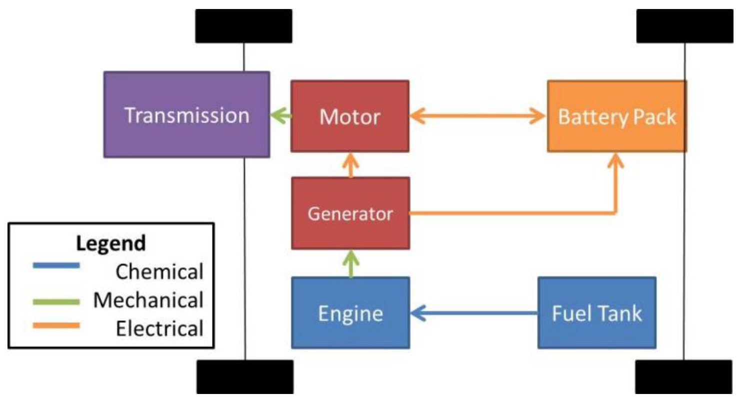

Figure 2.1: Series Hybrid Vehicle Architecture

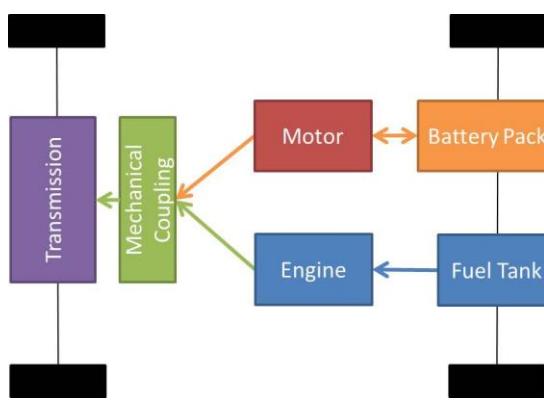

Figure 2.2: Parallel Hybrid Vehicle Architecture

A power split hybrid uses a planetary gear set to transmit power from the engine to the wheels. Power split is commonly used in hybrid vehicles on the market today because of the wide range of operating conditions possible. It allows the power to flow mechanically to the wheels or to the generator where the mechanical energy is converted into electrical energy so that the electric motor can propel the wheels [7]. The transmission is a key factor in power-split hybrids because of the variability of configurations possible. Figure 2.3 shows one possible power split configuration.

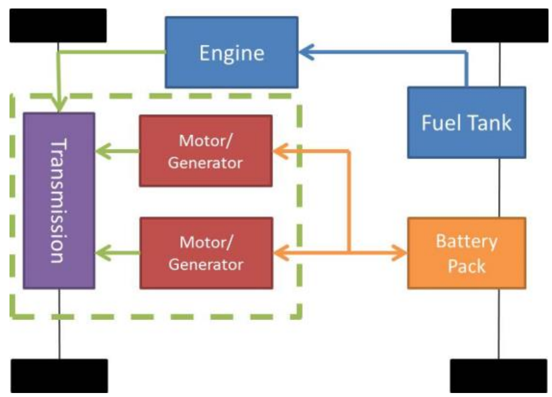

Figure 2.3: Power-split HEV with EVT

A common technology used is the electrically variable transmission (EVT). An EVT uses a planetary gear set where the torque and speed inputs can be applied to each part of the set in any combination [8]. Hybrid vehicles can use an EVT because it allows the vehicle to operate at any motor or engine speed operating point because there are no fixed gears like a traditional transmission. EVTs are used because of a possible increase in efficiency and an increased smoothness in driving as there is no transmission shifting [9]. An EVT will include a single set of planetary gears, which includes a sun gear, a carrier for planet gears, and a ring gear, and two electric motors and can be configured a number of different ways. One electric machine is used to control the speed ratio of the transmission. The ICE will be mechanically connected to the EVT. Figure 2.4 is a schematic of the GM 1-mode EVT with motor A connected to the sun gear and motor be connected directly to the output shaft [10].

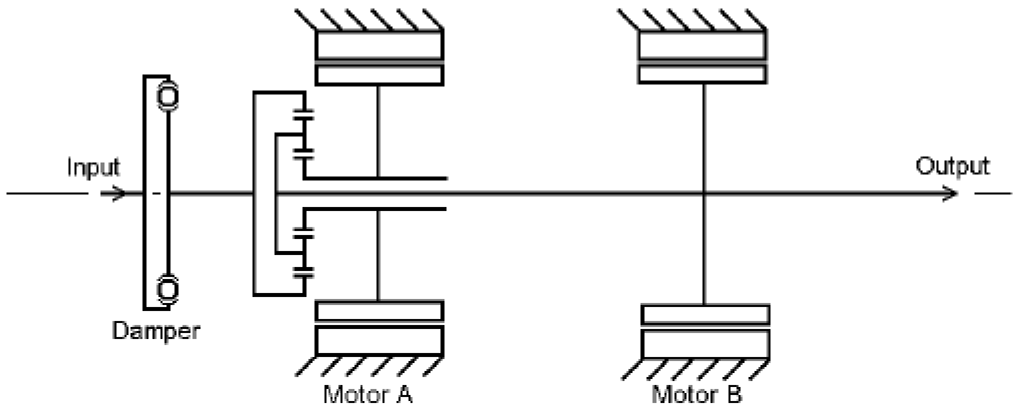

Figure 2.4: Schematic of GM 1-Mode EVT [10]

2.2 Types of Hybrid Vehicles

The capability of the HEV is based on the size and configuration of the battery pack and electric motors. The goal of HEVs is to reduce fuel consumption and tailpipe emissions by utilizing an electrified powertrain and developing an efficient energy management strategy. There are many common strategies and technologies used in HEVs including regenerative braking, engine start/stop, and using a downsized engine.

The hybrid vehicle spectrum ranges from mild hybrid to extended range electric vehicle. Each type of hybrids uses different technologies and has different advantages; however the overall goal of all of these vehicles is to improve the overall fuel economy of the vehicle. Traditional hybrids are generally categorized into mild or full hybrid and are charge sustaining vehicles.

The mild hybrid is, as the name suggests, the most basic implementation of hybrid technologies. Mild hybrids are electrified vehicles, but the vehicle is still driven by the ICE. The parallel powertrain includes a downsized ICE and a small electric motor, and a small battery pack. The main purpose of the electric motor is to allow the engine to be used more efficiently. Using the electric machine in combination with the engine allows the elimination of the engine operating at inefficient operating points. The engine wastes a great deal of fuel when the vehicle is idling. One of the biggest contributions to increased efficiency in mild hybrids comes from the engine start/stop system which allows the engine to turn off when the vehicle is stopped and then can be quickly restarted when the vehicle needs to move. A common start-stop system is a belted starter alternator where a small electric machine and battery pack are used to keep the car running while the engine is turned off and allows the engine to be restarted without having to restart the car. The electric machine and battery allow the engine to turn off when the vehicle is at rest. The electric motor can also provide extra power at points of extreme torque requests which can both assist the engine and allow it to operate at more efficient points. The vehicle cannot be propelled solely by the electric machine. The estimated fuel economy improvement for a mild hybrid is 10 to 20% [11].

The next step up from a mild hybrid is a full hybrid. Full hybrids are still only capable of charge sustaining operation and are generally parallel hybrids. They utilize the same fuel saving technologies as mild hybrids, but because of a larger battery and possibly more than one electric machine can include more efficiency improving technologies. The increased battery and electric machine size can allow full hybrids to drive at low speeds and for short distances using only electric power [11]. This capability allows HEVs to avoid using the engine in stop and go traffic or in urban driving. This can also allow a smaller engine to be used in the vehicle.

A PHEV is "a hybrid vehicle with the ability to store and use off-board electrical energy in the rechargeable energy storage system" [4]. A PHEV generally has a larger battery pack and electric machines with the ability to provide enough power to drive the vehicle in an all-electric mode. This categorizes it as a charge depleting hybrid. As the name suggests, the large battery can be charged while driving through regenerative braking, but must be plugged into an outlet to be fully charged. This all electric mode can range anywhere from a few miles to more than 40 miles depending on the battery size, driver, and route. Once the battery limit is reached, a PHEV will behave like a traditional HEV.

CHAPTER 3: CONTROLS DEVELOPMENT PROCESS

3.1 Overall Process

The software that controls the EcoCAR2 vehicle is developed in the MATLAB/Simulink environment. The controls development process utilized by the Ohio State EcoCAR 2 team, summarized in Figure 3.1, was based on the process used in the automotive industry. It includes three overall steps to ensure any control algorithm implemented on the vehicle will be safe and not cause any damage to components.

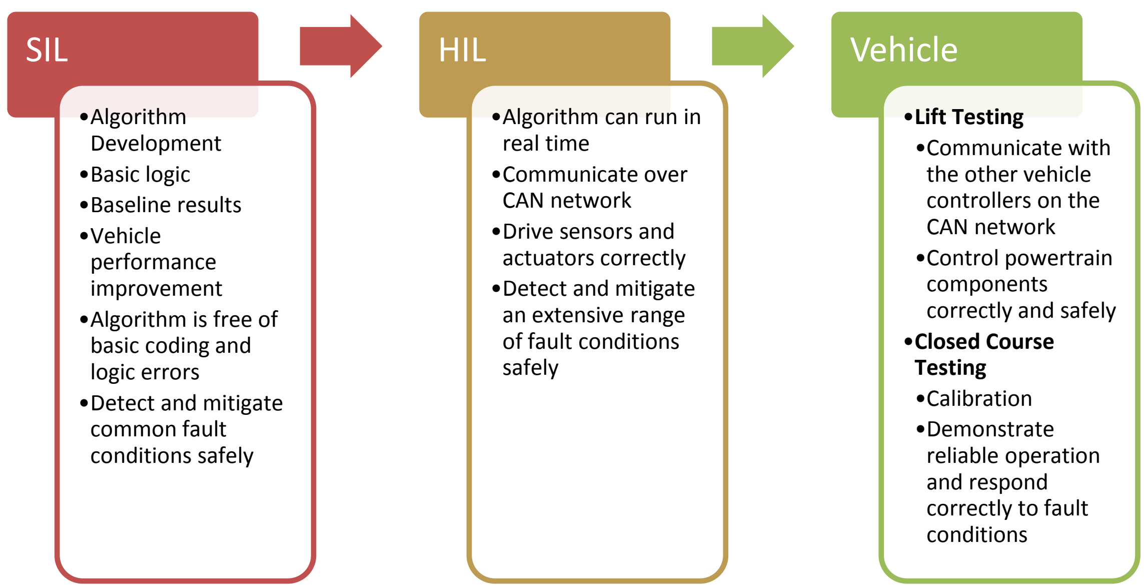

Figure 3.1: Controls Development Process

Any modification to the control structure or algorithm needs to be validated using the steps outlined in Figure 3.1. The actual algorithm development occurs in Software-in-the-Loop (SIL). Next the algorithm must be validated using Hardware in the Loop (HIL). Lastly, the algorithm is tested and calibrated in the vehicle. This is a rigorous process to ensure safe vehicle operation. Following this process can also minimize damaging critical components and help provide an overall understanding of vehicle operations.

3.2 Software-in-the-Loop

The first step in the controls development process is SIL. A vehicle SIL simulator will generally have a structure similar to the one shown in Figure 3.2

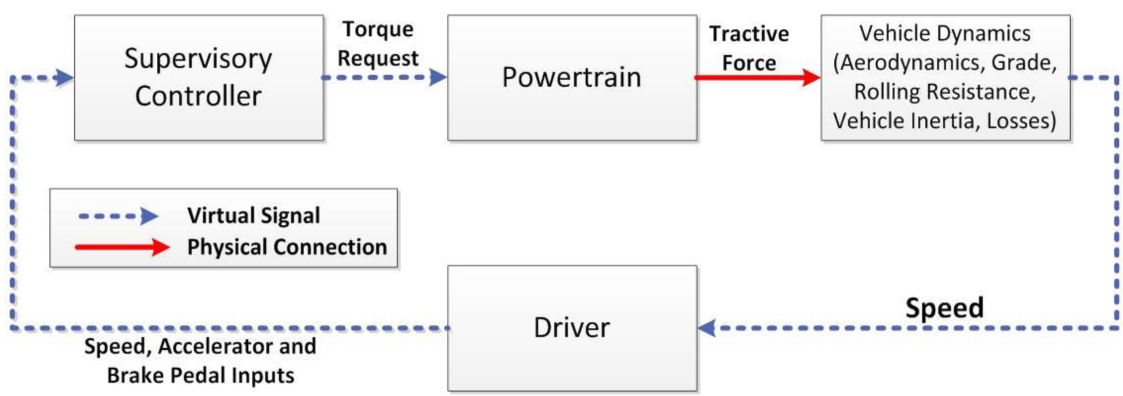

Figure 3.2: SIL Structure Overview

The SIL model includes the supervisory controller, powertrain, vehicle, and driver models. The powertrain model is an energy based model that includes all of the vehicle components. Each component has a model which can be simple or complex depending on the type of simulator and the amount of detail required by the controls testing. The supervisory controller calculates the torque request based on the pedal requests from the driver and the torque available in the vehicle operating mode. The powertrain model takes the component torque requests and calculates the amount of propulsion force provided by the engine and the electric machines. The vehicle model calculates the resistive forces acting on the vehicle such as, aerodynamics, grade, drag, rolling resistance, and vehicle inertias. The driver model takes the speed signal from the vehicle model and outputs the driver brake and accelerator pedal positions necessary to meet the speed trace.

The SIL model developed and used by the OSU EcoCAR 2 team is a lumped parameter energy model known as EcoSIM. EcoSIM has been developed and refined throughout various AVTCs over the last 15 years at Ohio State. EcoSIM utilizes the overall structure discussed above and can be adapted to different hybrid vehicle architectures. Once the powertrain model for a specific vehicle is developed, SIL is mainly used as a development tool for the supervisory control algorithm. The powertrain component models in EcoSIM are simplified static map based models. The engine and electric machine maps were developed based on data from component testing. The engine testing was done by the EcoCAR team and the electric motor testing was done by the motor manufacturer.

Both the mode selection and mode operation strategies are implemented in the supervisory controller, which then sends out torque requests and other control signals to the components or other vehicles controllers over the Controller Area Network (CAN). The algorithms for each operating mode are developed and initially tested in SIL. This step ensures that the control algorithm is free of basic coding and logic errors. SIL is also used for basic fault testing. The control algorithm must be able to detect and mitigate common fault conditions safely, such as a motor overspeed or unintended vehicle acceleration. The SIL model is also used to set Vehicle Technical Specifications (VTS), both performance and fuel economy targets. EcoSIM runs faster than real-time which allows for it to be helpful in the development process as control changes can be quickly implemented and tested.

While EcoSIM is a useful and powerful tool in the controls development process, it is important to understand the limitations of the model. As discussed above, in EcoSIM many of the components are modeled using simple maps or energy based equations. The maps are simplified to allow the model to run in a reasonable amount of time. With this reduced fidelity, the results can be used to validate basic control logic and functionality, but it is understood that the actual components may respond and interact differently in the vehicle. Secondly, using an energy based model does not account for component inertias and dynamics. Additionally, EcoSIM is unable to replicate the actual communication between the supervisory controller and component controllers. This means that often times it seems as though something like a gear shift is able to happen very quickly in simulation when, in reality, it takes a few seconds. It is possible to model some of the timing into the supervisory controller; however, often times this is just an approximation.

3.3 Hardware-in-the-Loop

Once a control algorithm meets the functional requirements in SIL, the next step is to validate it using the Hardware-in the-Loop simulator. The code is loaded onto the controller that will be in the vehicle and connected to the HIL through the CAN network. The plant model is simulated using a dSPACE HIL. The MicroAutoBox controller and HIL are connected through a CAN network similar to the one in the vehicle. The HIL is used to test control algorithms in real time and to ensure that signals are properly communicated over CAN. Other controllers such as the engine and transmission controllers can be connected to the HIL in addition to the supervisory controller. It also allows the possibility of connecting actual components, such as a throttle or the automated manual gear shifting cable, to do component level testing before it is in the vehicle and interacting with other components. The HIL is also used for more extensive fault testing.

Figure 3.3 Hardware-in-the-loop Test Bench

CHAPTER 4: ALGORITHM DEVELOPMENT

4.1 Acceleration Requirements

The overall goal of this project is to develop a vehicle operating mode for expected vehicle accelerations, both to maintain consumer acceptability for everyday driving and to successfully meet the 0-60 MPH and 50-70 MPH acceleration targets set by the competition. There is no official target for normal driving; however, the vehicle is expected to be able to meet the steep accelerations included in the standard EPA drive cycles (US06, FUDS, FHDS). The competition required acceleration events are 0-60 MPH and 50-70 MPH. Table 4.1 below shows the acceleration design targets as well as the competition requirement for each acceleration.

Table 4.1: Acceleration Requirements

Specification	Production 2013 Malibu	Competition Design Target	Competition Requirement
Acceleration 0-60 MPH	8.2 sec	9.5 sec	11.5 sec
Acceleration 50-70 MPH (passing)	8.0 sec	8.0 sec	10 sec

4.2 Defining Modes

In evaluating the various acceleration requirements and potential vehicle operating strategies that could be used to meet each requirement, it became clear that not one, but three strategies would need to be developed to meet all of the acceleration requirements. There were common factors between the strategies allowing for some common development and background testing to be done with modifications made to meet each specific goal. The overall vehicle restrictions remained the same whereas the actual mode operations differed. The entrance and exit conditions were also different for each strategy.

4.3 Vehicle Restrictions

In developing a vehicle performance mode it is important to take into account the limits each component being used. In this case the key limitations common to all three acceleration modes were the electric machine torque, electric machine speed, and battery discharge current. For battery discharge current and electric machine torque the peak operating limits were used initially since both the 0-60 and 50-70 MPH accelerations occur in about 12 seconds.

4.3.1 Electric Machines

The limitations on the electric motors were torque and motor speed. The performance of an electric machine can be represented through its torque-speed curve or efficiency map. The front and rear electric motors are the same size and therefore have similar torque-speed curves. The difference in output torque to the wheels comes from the FEM being connected through a six speed transmission and the REM through a single speed gearbox. Figure 4.1 shows the peak and continuous maximum motor torque-speed curves for each of the electric motors. Electric machines have a constant torque region at lower speeds and a constant power region. Since the goal is to be able to get the maximum torque from the electric motors, it was important to try to say in the constant torque region of the motor operating map where the peak motor torque is 180 Nm. The motors are able to operate at peak torque for at most 10 seconds. Operating at peak for any longer than 10 seconds can cause the motor temperature to increase to unsafe levels. In Figure 4.1, the REM peak torque curve varies from the FEM peak torque curve above 4000 RPM. The REM peak torque curve was limited to the REM continuous torque curve above 4000 RPM after vehicle testing by the EcoCAR team determined that the REM could be unstable above that point.

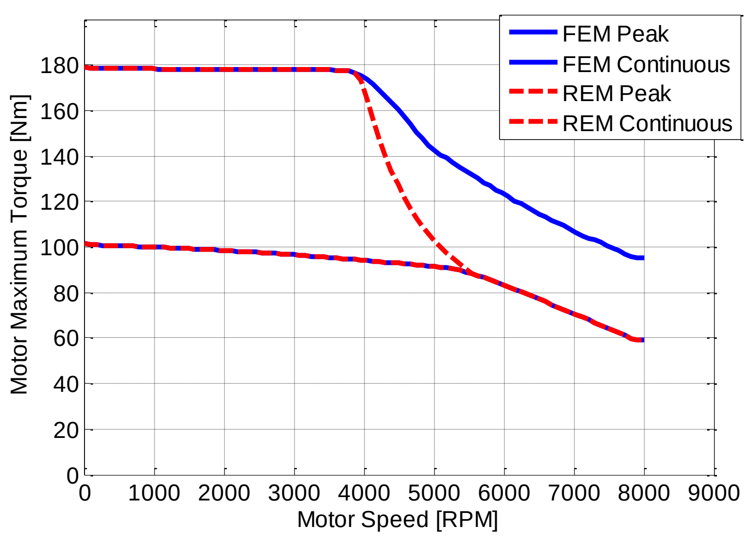

Figure 4.1: Electric Machine Maximum Motor Torque Curves

Figure 4.2 shows the maximum axle torque possible at each gear. Third gear allows the FEM to provide the most torque to the axle; however, the motor is unable to safely operate at this speed. Figure 4.3 shows the maximum motor speeds at each gear and the corresponding vehicle speed. For the 0-60 MPH (96 KPH) run, the FEM is fixed into a single gear. In order to be able to operate up to 96 KPH, fifth gear was selected to avoid causing an FEM overspeed fault. The motors overspeed above 6000 RPM, but the FEM is limited to around 4000 RPM because of the mechanical limits on the bearings. The difference in vehicle acceleration time in fourth and fifth gear is discussed in the results section.

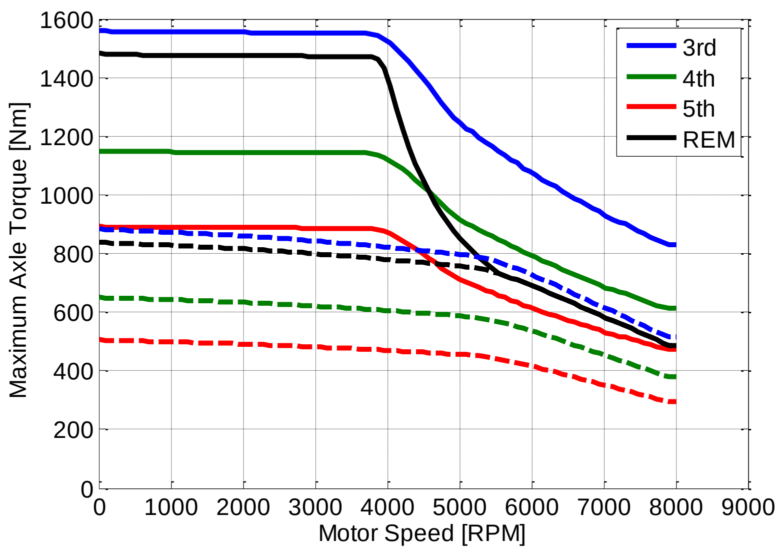

Figure 4.2: Electric Machine Maximum Axle Torque

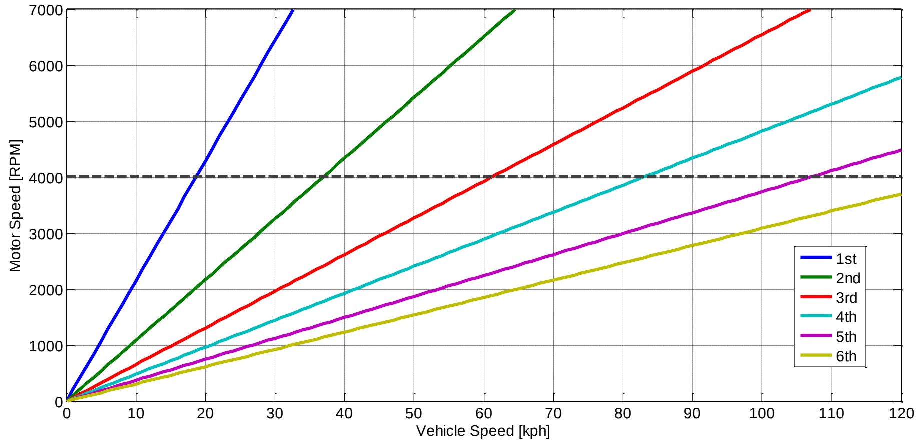

Figure 4.3: FEM Motor Speeds

4.3.2 Battery Current Limitations

When operating at peak torque, the electric machines are capable of requesting large amounts of current from the battery pack. If too much current is requested too quickly or for too long the battery contactors will open and the vehicle will shut down. To avoid vehicle failure, there are a number of battery limits in place. Most of the limits will change based on whether the current requested is continuous or a short pulse. The first limit is the battery discharge limit, shown in Figure 4.4, which is constant over a wide range of SOC. The peak current discharge limit is 612 amps while the continuous discharge limit is 180 amps. When both electric motors are operating a maximum torque and therefore using a great deal of discharge current, it is possible to get close to this peak limit. Another set of safeguards are the battery fuses. There are two regular fuses, 350 amps and 400 amps, and one slow blow fuse. At 10 seconds, which is the amount of time the electric machines can operate in peak, the normal fuses are safe up to 1000 amps. The battery discharge current in Figure 4.4 is data collected during a 0-60 MPH acceleration test. The value exceeds the continuous current limit, but does not reach the peak current limit.

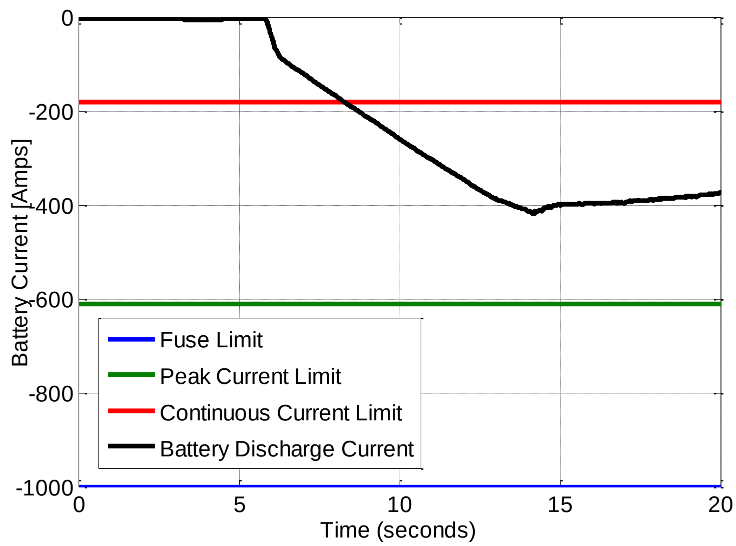

Figure 4.4: Peak Battery Current Limits

A second limit is the battery current discharge buffer. This is a constantly calculated limit based on battery SOC, charge and discharge current, battery pack temperature, and recent operation of the vehicle. The battery manufacturer A123 has developed a specific discharge buffer for safe use of the battery pack used in the EcoCAR vehicle. The discharge buffer value starts at 100% and decreased as current is requested from the battery. The rate at which the buffer decreases depends on the amount of current requested. Figure 4.5 shows an example of how the discharge buffer and current vary during a 0-60 MPH acceleration test.

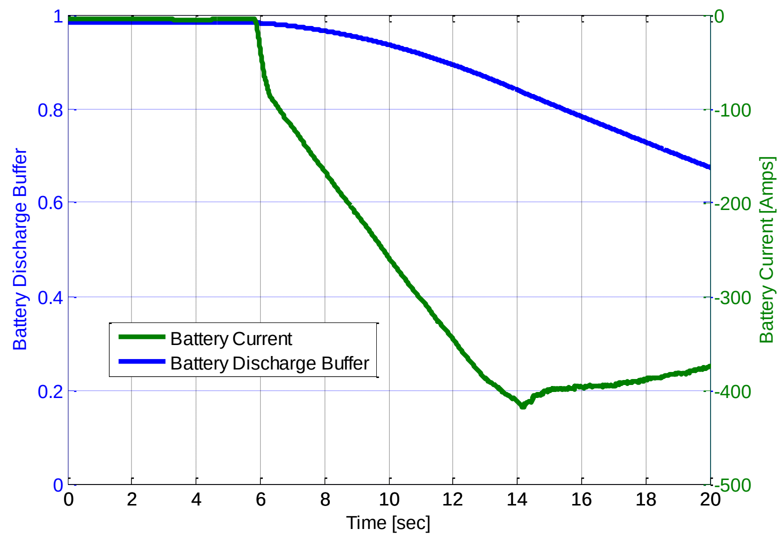

Figure 4.5: Vehicle Battery Discharge Buffer and Battery Current

Under completely ideal conditions the battery would be able to operate at peak discharge for a maximum of 10 seconds. This ideal case would be if the vehicle had been at rest for an extend period of time so the discharge buffer was at 100% and then the peak current was requested. When the discharge buffer reaches 0, the battery contactors will open. The OSU EcoCAR control strategy uses the discharge buffer to limit the driver's torque request when the buffer is less than 10%. This reduces the amount of discharge current requested and slows reaching the minimum value of the discharge buffer. This limit is the most important factor in developing the acceleration mode because when operating at peak conditions the discharge buffer is highly likely to rapidly decrease even if the battery discharge current is nowhere near reaching any of the other limits.

4.4 Mode Entrance and Exit

For each acceleration mode it was important to determine when the vehicle would enter and exit. Figure 4.6 shows the mode transitions. The entrance conditions are mainly based on accelerator pedal position because as the driver increase the accelerator pedal position they expect a certain rapid response. Since the acceleration modes are mostly all electric, low battery SOC and brake pedal position are generally used as exit conditions. The everyday acceleration and 0-60 MPH acceleration modes are both entered from the CD normal driving mode. To enter the 0-60 MPH acceleration mode the battery SOC must be greater than 35% and the accelerator pedal position must be greater than 80%. To exit the mode, the brake pedal can be pressed or the battery SOC can drop below 20%.

With everyday acceleration, the entrance and exit conditions were important because the goal of this mode was to improve performance without completely sacrificing efficiency. With this goal in mind, the entrance and exit conditions tried to take into account when it was really necessary to enter the mode for better acceleration and avoid too much mode shifting. To enter, the accelerator pedal must be greater than 30% and SOC greater than 30%. The 30% accelerator pedal threshold was set based on the acceleration requirements of the FUDS and US06 drive cycles. There is no need to remain in this mode if the accelerator pedal has dropped below the threshold for more than 15 seconds or the standard exit condition that the brake pedal has been pressed or the SOC drops below 30%.

Lastly, to enter the 50-70 MPH mode the vehicle must be in charge sustaining mode with the engine on. The vehicle speed must be above 40 MPH, accelerator pedal must be greater than 70% and the transmission should be in fifth gear. While the mode can operate at lower speeds it will exit the mode if vehicle speed drops below 40 MPH or the brake pedal is pressed.

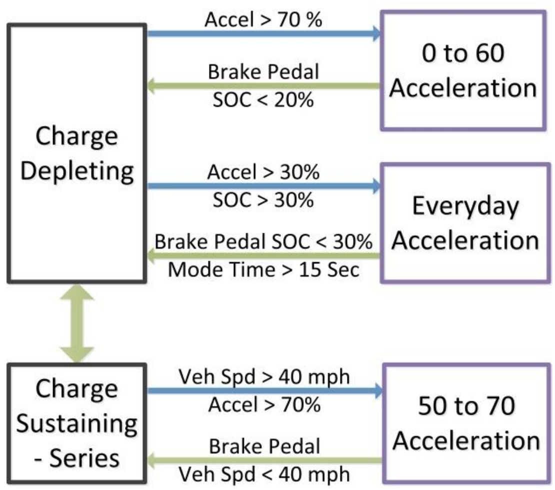

Figure 4.6: Mode Transitions

4.5 Mode Operation

Each acceleration strategy was developed under ideal circumstances and then modified based on component restrictions. For 0-60 MPH acceleration the strategy was simple, use the electric machines to obtain the most torque output possible. The front electric machine is capable of a greater torque output than the engine and ideally has a faster response time. A second strategy of this mode was to operate in a fixed gear to eliminate the time required to shift gears.

At higher speeds, the front electric machine is unable to provide more torque than the engine. For this reason a combination of the Engine and FEM was used for 50 to 70 MPH acceleration. The main limitations were the maximum torque of the engine and the maximum input torque to the transmission.

The third acceleration mode is less of a mode than an improvement to the normal CD driving mode. The goal of the everyday improvement was to improve the vehicle response to accelerator pedal input to improve the driving experience. This mode uses both electric machines operating near their peak operating conditions instead of being limited by what is the most efficient operating condition at that point in time.

CHAPTER 5: ACCELERATION MODE RESULTS

5.1 0-60 MPH Acceleration

With a basic acceleration strategy and defined component restrictions, it was possible to implement each acceleration strategy in both SIL and HIL. For each mode the baseline and ideal cases were evaluated. Next component restrictions were incorporated one at a time to evaluate the effect of each restriction on the acceleration time. The acceleration time for each iteration of the 0-60 acceleration algorithm is included in Table 5.1.

Table 5.1: 0-60 Acceleration Times

Limits on Acceleration	SIL Time (Seconds)	HIL Time (Seconds)
Baseline – no acceleration mode	12.9	----
No limits	8.7	----
Speed Limit – 4th gear	9.3	----
Speed Limit – 5th Gear	10.7	10.8
Estimated Discharge Buffer	11.9	11.5

The baseline 0-60 MPH acceleration was completed in the normal CD mode and included a gearshift in the middle of the run. The gear shifting time was included in the baseline by approximating that a case gear shift would take about four seconds. Because of the associated with gear shifting, a fixed gear strategy was investigated for accelerating. The baseline 0-60 acceleration was 12.9 seconds.

The second 0-60 MPH run was a model with almost no component restrictions. Figure 4.2 shows that the most available FEM torque would be in third gear. Under ideal conditions, the vehicle is able to acceleration from 0-60 MPH in 8.7 seconds. Third gear may be the most ideal gear to allow the FEM to deliver torque to the wheels; however, in third gear the FEM would have to operate at a very high speed to be able to reach 60 MPH. Figure 5.1 shows the comparison between accelerating in a fixed fourth or fifth gear instead of the normal CD mode.

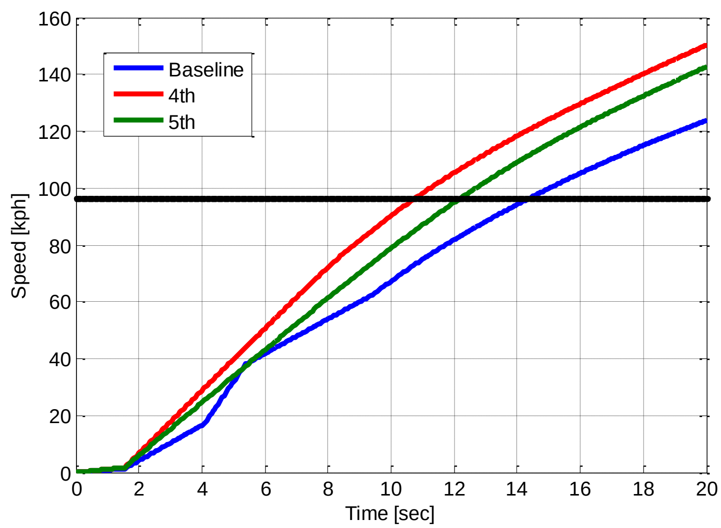

Figure 5.1: 0 to 60 MPH Acceleration in Different Gears

Fixed fourth gear was able to improve upon the baseline acceleration time by 3.6 seconds and fixed fifth gear was able to improve acceleration by 2.2 seconds. From electric machine testing in the vehicle, it was discovered while the motors can be used up to a speed of 6000 RPM, the REM is not stable at high speeds. The motor speeds were also limited by the bearings. To avoid operating in a potentially unsafe speed region, the fixed gear selected was fifth gear keeping the maximum FEM speed around 4000 RPM. Figure 5.2 shows the difference in motor torque for 0-60 acceleration in CD and fixed fifth gear. In the baseline case, both electric machines begin operating 20 Nm below the acceleration mode operation because in charge depleting mode the control strategy is focused on operating at the most efficient points instead of outputting the most torque possible. The loss of FEM torque during the gear shifting is also apparent. In the baseline case the REM only operates at its peak torque for about a second of the 12 seconds run.

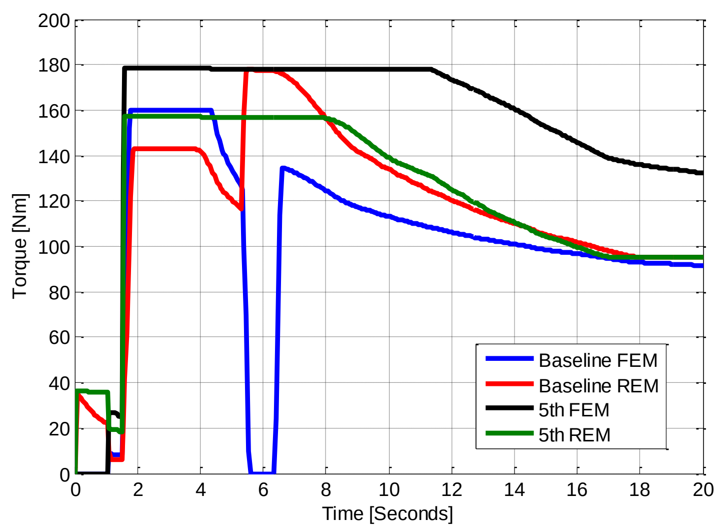

Figure 5.2: Motor Torque During 0-60 Acceleration

Another limitation on acceleration is that the motors cannot operate at peak conditions for longer than 10 seconds because of the limits on battery discharge current. In EcoSIM it was not possible to take the discharge buffer into account because of the lack of a correct battery current calculation from the simple battery model. Instead, the acceleration strategy was modified to ensure that the peak torque was not requested for more than 10 seconds. Figure 5.3 shows the new strategy where after operating at peak for 8 seconds both the FEM and REM are limited to operating at their maximum continuous torque curve. This was done to reduce the risk of reaching the battery discharge buffer limit causing the battery contactors to open.

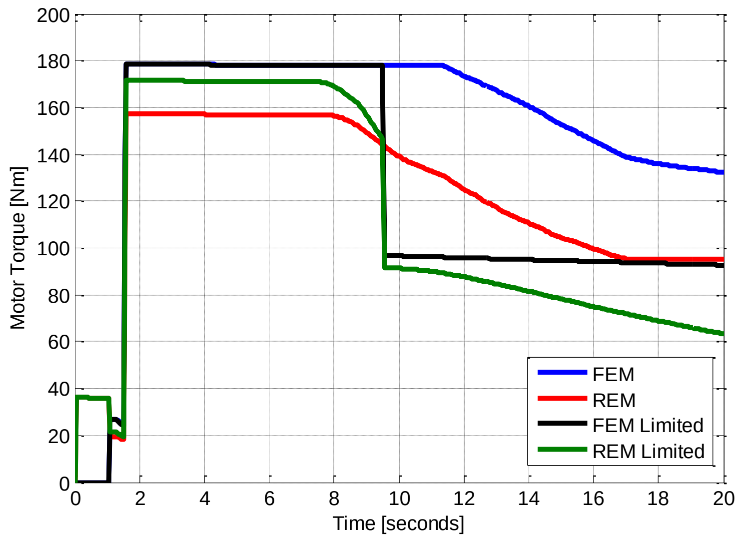

Figure 5.3: 0-60 MPH Acceleration Motor Torque with Pulse Current Limited

HIL testing in fixed fifth gear showed little difference from the SIL model increasing the acceleration time from 10.7 seconds to 10.8 seconds. This was expected as most of the component models on the HIL are the same as in EcoSIM. There were also no complex timing or communication issues that would need to be tested on the HIL. The HIL model does include a more complex battery model, developed by A123 and dSPACE, with a more accurate battery current calculation. This allowed for an estimation of the discharge buffer to be made. The discharge buffer was modeled with by an integrator on the current and a gain that was tuned based on actual vehicle test data from an attempted 0-60 MPH acceleration test. With this data it was possible to estimate how the discharge buffer would change with respect to the discharge current shown in Figure 5.4

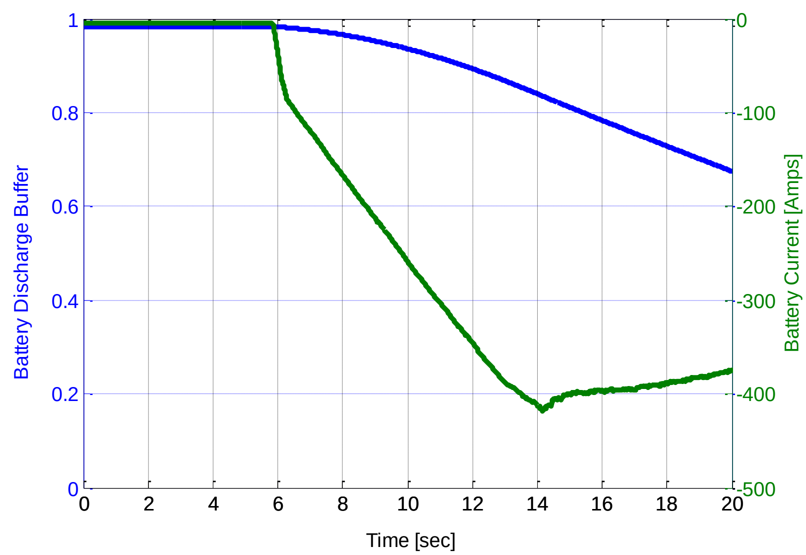

Figure 5.4: HIL Discharge Buffer Estimation

When the discharge buffer decreases the maximum rear axle torque is reduced, with the result being an increased acceleration time of 11.5 seconds. Figure 5.5 shows the difference between the torque requests for the fixed gear version of acceleration in SIL and the discharge buffer applied to the HIL model.

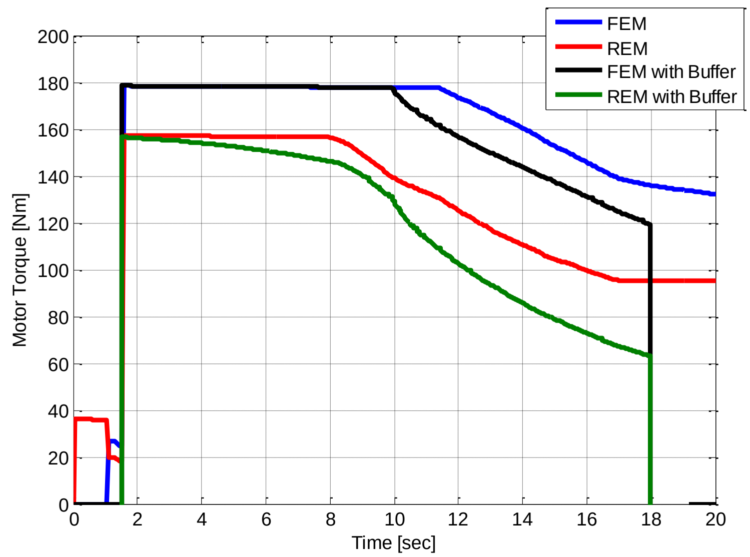

Figure 5.5: HIL 0-60 Acceleration with Discharge Buffer Approximation

The final iteration of the 0-60 MPH acceleration mode in included a constant torque split to the front and rear motors is based on the total torque requested and the maximum torque that each can provide to the wheels. The peak torque request is limited by the amount of time that the vehicle has been in acceleration mode, which will be tuned on the vehicle where the discharge buffer is calculated and not estimated.

5.2 50-70 MPH Acceleration Mode

A similar process was followed in developing the 50-70 MPH acceleration mode. The baseline run for 50-70 MPH was done with the vehicle in CD mode using only the electric machines. The 50-70 acceleration times at each development step are included in

Table 5.2. The baseline acceleration was 5.7 seconds. As discussed in the requirements section, the electric machines have a speed limit and in order to meet the 50-70 MPH speeds the FEM would need to operate in fifth or sixth gear limiting the amount of torque available at the wheels. To supplement the electric machine torque, the engine was used in a parallel configuration to achieve the desired 50-70 MPH acceleration target. The ideal case for passing acceleration included the FEM in fifth gear at maximum torque, the engine set to a constant output torque of 140 Nm, and the REM operating at peak torque. In this ideal operating mode the vehicle was able to accelerate form 50-70 MPH in 3.45 seconds.

Table 5.2: 50-70 MPH Acceleration Times

Limits on Acceleration	50-70 Time (Seconds)
Baseline – CD	5.65
No Limits	3.45
Transmission input limit	4.3
HIL	4.8

A new limitation to consider for this mode is the maximum input torque to the transmission. The FEM by itself is not capable of exceeding the 320 Nm transmission input shaft torque limit. At the peak torque of the FEM, the input to the transmission is 311 Nm. If both the engine and FEM are operating at their maximum torque in parallel, the torque input to the transmission is about 460 Nm which is 140 Nm over the maximum allowable transmission input torque. Because of the concerns of operating the motors at high speeds or their peak torque for an extended period of time, for this mode all of the torque available from the engine was used and then the FEM was used to supplement. The REM is operating the same as in the other acceleration mode. Figure 5.6 shows the torque split between the components as well as the mode transition into the 50-70 acceleration mode. The engine torque was set to 135 Nm and the FEM torque was set to 100 Nm with the transmission in fifth gear. This makes the input to the transmission 310 Nm. With the transmission input shaft limit the passing acceleration is 4.3 seconds.

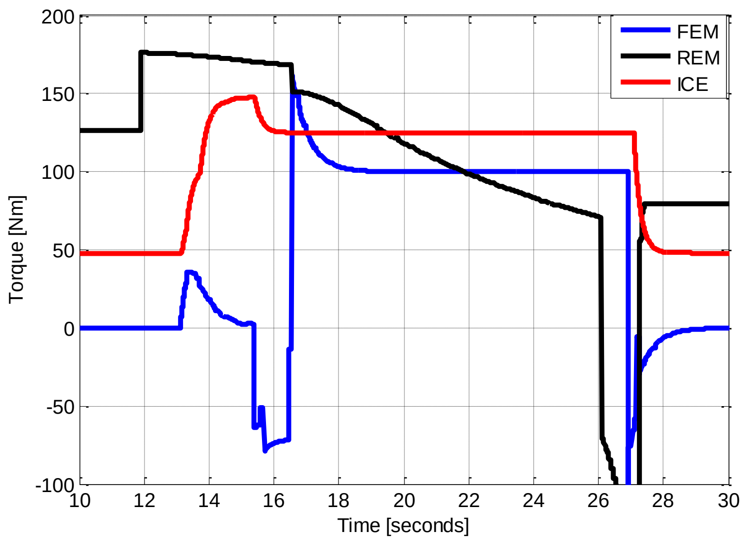

Figure 5.6: 50-70 Acceleration Component Torque

Since this acceleration strategy uses the engine, the low speed acceleration happens in charge sustaining series, so that the engine has time to warm up, and the vehicle transitions into the parallel acceleration mode at 35 MPH. The HIL model includes the same discharge buffer estimation used for 0 to 60 acceleration mode. The effect of the discharge buffer can be seen in the REM torque in Figure 5.6. Using series mode to get to 35 MPH uses a great deal of the discharge buffer severely limiting the torque available for the REM when it is really needed. This should not be a problem in the actual vehicle because the acceleration event starts with the vehicle at 45 MPH. The acceleration for the HIL model including the discharge buffer is 4.8 seconds.

5.3 Everyday Acceleration

The last acceleration mode considered was an everyday acceleration mode. The goal of this mode was to improve the response in normal acceleration conditions such as accelerating from a stoplight or onto the freeway. This mode was developed to be a supplement to the normal charge depleting operating mode. With everyday acceleration, the important aspect was determining when it would actually be beneficial to enter the mode. As discussed previously, entrance to this mode was based on the accelerator pedal position.

The strategy for this mode was similar to the other two acceleration modes in that the mode operation includes a fixed gear with a static torque split providing the maximum amount of torque possible at that point. However, for everyday driving picking a single fixed gear would be challenging unless the acceleration mode also included a vehicle speed limit. Since the vehicle would often already be in forth or sixth gear there are two possible acceleration sub-modes to enter to limit gear shifting. Both have a static torque split based on the maximum possible motor put and are fixed into forth or sixth gear depending on the current gear. The sixth gear acceleration is important for higher speed accelerations that would be necessary when driving at highway speeds.

The goal was to evaluate the effectiveness of this mode by using the FUDS, US06, and LA92 drive cycles. In SIL development of the mode it became clear that there were two problems with this approach. First, while the selected drive cycles are supposed to be representative of everyday driving, the vehicle is expected to be able to meet velocity trace for the EPA cycles. While the LA92 drive cycle includes more aggressive accelerations, it was not useful in evaluating and tuning the everyday acceleration mode.

The second development problem came from EcoSIM itself. In EcoSIM, the driver model takes the speed from the vehicle model and outputs accelerator and brake pedal position. Generally, to have a stable model for development, the driver model is tuned to be a conservative driver. As shown in

Figure 5.7 even the normal CD mode is not able to exactly follow the velocity profile. The type of consumer who would notice an acceleration mode would most likely be a more aggressive driver. Ideally, an everyday driving mode would need to be validated for logic in SIL, but calibrated in the vehicle on normal roads. The success or failure of the acceleration mode would be a subjective opinion based on the customer driving the vehicle.

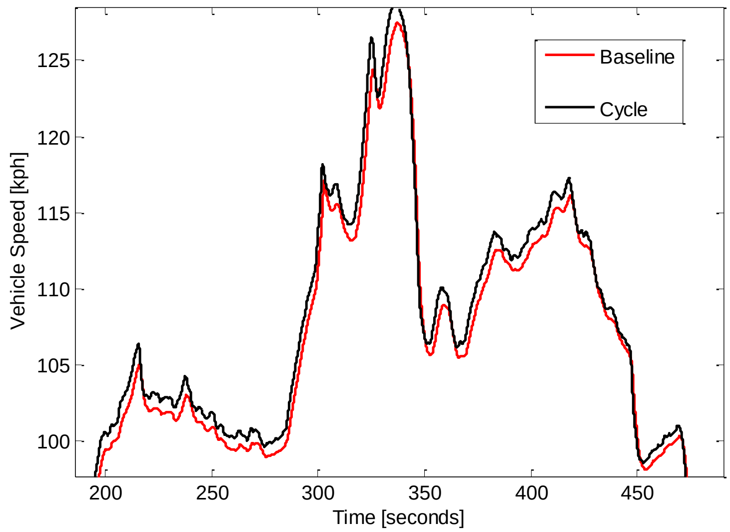

Figure 5.7: US06 Drive Cycle Simulation Velocity Differences

Taking into account that this mode was all electric, it was possible to obtain the change in charge depleting range and charge depleting energy consumption to quantify the potential impact acceleration mode could have on efficiency. One way to calculate energy consumption statistics is to use four drive cycles (505, US06 City, HWFET, US06 HWY) and record the energy consumption and change in SOC over one cycle, included in Table 5.3. As expected, when the vehicle is driven more aggressively and is not trying to operate at the most efficient points, more energy will be used over the same drive cycle.

Table 5.3: Energy Consumption for Normal Vehicle Operation and Acceleration Mode

	Normal CD Operation	**Acceleration Mode**
CD Range [km]	97.5	90.65
CD Energy Consumption [Wh/km]	176.3	182.5

CHAPTER 6: FUTURE WORK AND CONCLUSIONS

6.1 Future Work

The scope of this project was to develop the acceleration modes and validate them on the HIL. The next step in the controls development process is validating that each new mode has the expected result on the car. For the next steps only the 0-60 and 50-70 acceleration modes will be continued to be developed, because there was no clear benefit seen in the SIL development of the everyday acceleration mode. This does not mean that there is no place for performance in consumer HEVs, it was just not in the scope of the EcoCAR 2 project.

For further developing 0-60 and 50-70 acceleration the next step is correcting the transmission model in SIL and confirming that fifth gear can still be used. This must be done because late in the progress of this project the EcoCAR team discovered that the transmission gear ratios were different than originally thought. The change should not have a big impact on the acceleration mode algorithms. Once the new algorithm is re-validated in SIL and HIL, vehicle testing will be done on the chassis dynamometer. This step is important to make sure that the vehicle can correctly transition into each mode. Lastly track testing will be done at TRC to determine the actual benefit to including each acceleration mode as part of the overall control algorithm.

The development process followed in this project will be helpful in the development of future advanced vehicle design competitions. Specifically the analysis of individual component requirements will be beneficial to complete at the beginning of the project instead of towards the end when all components are integrated into the vehicle. Evaluating the component limitations in the vehicle development phase could allow vehicle components to be sized for both efficiency and vehicle performance. The initial assumption at the start of this project was that the main limit to acceleration was the maximum electric machine torque; however, the batteries actually imposed the most limitations to acceleration.

6.2 Conclusions

The goal of this research project was to follow the EcoCAR controls development process to develop an acceleration strategy for the OSU EcoCAR 2 PHEV. The project was divided into three separate acceleration modes as the strategies to meet each target began to differ. The three acceleration modes were 0-60 MPH, 50-70 MPH, and everyday acceleration. Each mode was developed using the EcoSIM SIL simulator. The acceleration modes were developed to operate at the vehicle's maximum operating points highlighting the need to evaluate the maximum safe operating conditions for the electric machines, battery, and transmission.

After taking into account all vehicle restrictions, each mode was evaluated on the HIL. The final 0-60 MPH acceleration time was 11.5 seconds and the final 50-70 MPH acceleration time was 4.8 seconds. Each of these times did improve upon the baseline acceleration time. In the scope of this project it was not possible to prove whether the new everyday acceleration would have a positive effect on driving.

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ADDITIONAL RESOURCES

Below are resources used for background information, but not cited in the paper.

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APPENDIX: LIST OF SYMBOLS AND ABBREVIATIONS

AVTC	Advanced Vehicle Technology Competition
CAFE	Corporate Average Fuel Economy
CAN	Controller Area Network
CD	Charge Depleting
CS	Charge Sustaining
DOE	Department of Energy
E85	85% ethanol and 15% gasoline fuel by volume
EPA	Environmental Protection Agency
EV	Electric Vehicle
FEM	Front Electric Machine
HEV	Hybrid Electric Vehicle
HIL	Hardware-in-the-Loop
HWFET	Highway Fuel Economy Test

ICE	Internal Combustion Engine
mpgge	Miles per Gallon Gasoline Equivalent
PHEV	Plug-in Hybrid Electric Vehicle
REM	Rear Electric Machine
SIL	Software-in-the-Loop
SOC	State of Charge
UDDS	Urban Dynamometer Driving Schedule
WTW GHG	Well-to-Wheel Greenhouse Gases